3 The uncertain future of the coasts

> It is now accepted that global warming will result in a significant sea-level rise in future, with many low-lying coastal areas around the world being lost to the sea over the coming centuries. The wealthy industrialized countries will be able to defend themselves from the encroaching waters for a time, albeit with massive technological effort. In the long term, however, they too will have to withdraw back from the areas under threat or, alternatively, adapt to rising water levels.

Sea-level rise – an unavoidable threat

> Since the end of the last ice age to the present day, sea level has risen by around 125 metres. This has natural as well as man-made causes. However, the human-induced greenhouse effect is intensifying this process. Its main effects are thermal expansion of water and melting of glaciers. This could result in the sea level rising by a further 5 metres within just 300 years.

Loss of habitats and cultural treasures

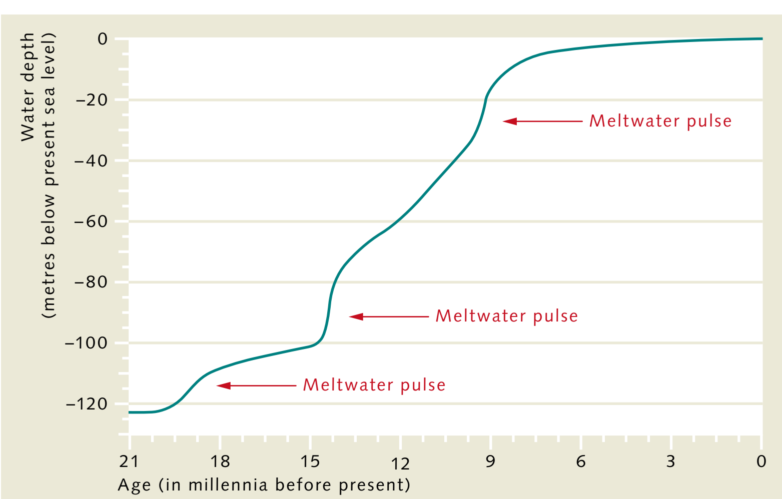
Sea-level rise is one of the most serious consequences of global warming. No one can really imagine how the coasts will look if the waters rise by several metres over the course of a few centuries. Coastal areas are among the most densely populated regions of the world and are therefore particularly vulnerable to the impacts of climate change. They include major agricultural zones, conurbations and heritage sites. How will climate change affect their appearance?

Researchers around the world are seeking answers to the question of how rapidly, and to what extent, sea level will rise as a consequence of climate change. In doing so, they must take account of the fact that sea level is affected not only by the human-induced greenhouse effect but also by natural processes. Experts make a distinction between:

- eustatic causes: this refers to climate-related global changes due to water mass being added to the oceans. The sea-level rise following the melting of large glaciers at the end of ice ages is an example of eustatic sea-level rise;
- isostatic (generally tectonic) causes: these mainly have regional effects. The ice sheets formed during the ice ages are one example. Due to their great weight, they cause the Earth's crust in certain regions to sink, so sea level rises relative to the land. If the ice melts, the land mass rises once more. This phenomenon can still be observed on the Scandinavian land mass today.

Sea level can change by 10 metres or so within the course of a few centuries and can certainly fluctuate by more than 200 metres over millions of years. Over the last 3 million years, the frequency and intensity of these fluctuations increased due to the ice ages: during the colder (glacial) periods, large continental ice sheets formed at higher latitudes, withdrawing water from the oceans, and sea level decreased dramatically all over the world. During the warmer (interglacial) periods, the continental ice caps melted and sea level rose substantially again.

The last warmer (interglacial) period comparable with the current climatic period occurred between 130,000 and 118,000 years ago. At that time, sea level was 4 to 6 metres higher than it is today. This was followed by an irregular transition into the last colder (glacial) period,



3.1 > Until 6000 years ago, sea level rose at an average rate of approximately 80 cm per century, with occasional sharp increases. There were at least two periods, each lasting around 300 years, when sea level rose by 5 metres per century. This was caused by meltwater pulses.

3.2 > Every time there is a storm, the North Sea continues its relentless erosion of the coast near the small English town of Happisburgh. The old coastal defences are largely ineffective. Here, a Second World War bunker has fallen from the eroded cliffs, while elsewhere along the coast, homes have already been lost to the sea.

with the Earth experiencing its Last Glacial Maximum (LGM) 26,000 to 20,000 years ago. At that time, sea level was 121 to 125 metres lower than it is today. Then the next warmer period began and sea level rose at a relatively even rate. There were, however, intermittent periods of more rapid rise triggered by meltwater pulses. These were caused by calving of large ice masses in the Antarctic and in the glacial regions of the Northern hemisphere, or, in some cases, by overflow from massive natural reservoirs which had been formed by meltwater from retreating inland glaciers. This relatively strong sea-level rise continued until around 6000 years ago. Since then, sea level has remained largely unchanged, apart from minor fluctuations amounting to a few centimetres per century.

Measured against the minor changes occurring over the last 6000 years, the global sea-level rise of 18 cm over the course of the last century is considerable. Over the past decade alone, sea level rose by 3.2 cm, according to measurements taken along the coast in the last century and, since 1993, satellite monitoring of the elevation of land and water surfaces worldwide (satellite altimetry). Admittedly, these are only short periods of time, but the measurements nonetheless point to a substantial increase in the rate of sea-level rise. Experts differ in their opinions about the extent to which specific factors play a role here:

- Between 15 and 50 per cent of sea-level rise is attributed to the temperature-related expansion of seawater;
- Between 25 and 45 per cent is thought to be caused by the melting of mountain glaciers outside the polar regions;
- Between 15 and 40 per cent is ascribed to the melting of the Greenland and Antarctic ice caps.

Based on the monitoring data and using computer modelling, predictions can be made about future sea-level rise, such as those contained in the latest Report by the Intergovernmental Panel on Climate Change (IPCC, 2007). This is the most up-to-date global climate report currently available, and it forecasts a global sea-

Sea-level rise
Sea-level rise has various causes. Eustatic rise results from the melting of glaciers and the discharge of these water masses into the sea. Isostatic rise, on the other hand, is caused by tectonic shifts such as the rise and fall of the Earth's crustal plates. Thermal expansion, in turn, is caused by the expansion of seawater due to global warming.

3.3 > Tourists preparing to abseil off the edge of the Ross Ice Shelf in Antarctica. Greater melting of the mass of floating ice that forms ice shelves could result in an increase in the calving rate of glaciers if the ice shelf is no longer there to act as a barrier.

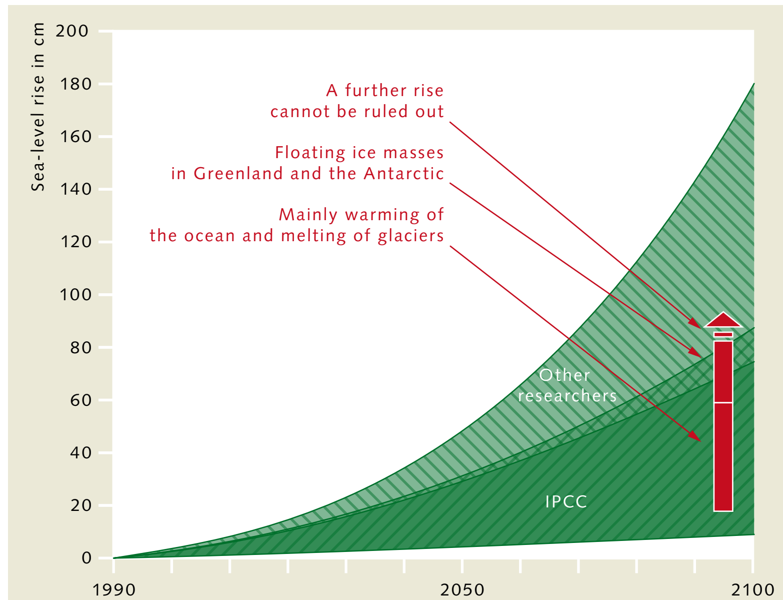
level rise of up to 59 cm by 2100. This does not take into account that the large continental ice masses (i.e. primarily the Greenland and Antarctic ice sheets) could melt more rapidly as a result of global warming. In fact, current satellite monitoring around the edges of the Greenland ice sheet, West Antarctica and the mountain glaciers outside the polar regions shows that the height of the glaciers and hence the volume of ice are decreasing faster than experts had previously assumed. These data and computer modelling suggest that sea level could actually rise by more than 80 cm, and perhaps even by as much as 180 cm by the end of this century. The melting of the Antarctic and Greenland glaciers is likely to intensify well into the next century and beyond. The other mountain glaciers will already have melted away by then and will no longer contribute to sea-level rise.

The German Advisory Council on Global Change (WBGU) expects a sea-level rise of 2.5 to 5.1 metres by 2300. The reason for the considerable divergence in these figures is that the climate system is sluggish and does not change at an even or linear rate, so forecasts are beset with uncertainties. What is certain is that the sea-level rise will accelerate slowly at first. Based on the current rate of increase, sea level would rise by just under 1 metre by 2300.

The present rise is a reaction to the average global warming of just 0.7 degrees Celsius over the past 30 years. However, the IPCC Report forecasts a far greater temperature increase of 2 to 3 degrees Celsius in future. This could produce a sea-level rise at some point in the future that matches the level predicted by the German Advisory Council on Global Change.

As with all climate fluctuations that have occurred in the Earth's recent history, the global warming now taking place will increase temperatures in the polar regions more strongly than the global mean and will therefore significantly influence sea-level rise. The stronger warming at higher latitudes is caused by the decrease in albedo, i.e. the surface reflectivity of the sun's radiation: as the light-coloured, highly reflective areas of sea ice and glaciers shrink, more dark-coloured soil and sea surfaces are revealed, which absorb sunlight to a far greater extent. If most of the continental ice sheets in Greenland and West Antarctica melt, sea level could increase by as much as 20 metres over the course of 1000 years in a worst-case scenario.

In West Antarctica in particular, the marginal glaciers are becoming unstable as a result of flow effects, and are exerting pressure on the ice shelves floating on the sea. This could result in the ice shelf breaking away from the grounded ice to which it is attached, which rests on bedrock and feeds the ice shelf. This would ultimately result in the glaciers calving, as the ice shelf would no longer be there to act as a barrier. Furthermore, even with only a slight sea-level rise, marginal grounded ice masses could break away in significant amounts due to constant underwashing by the rising water.



3.4 > Sea level will rise significantly by the end of this century, although the precise extent to which it will rise is unclear. The Intergovernmental Panel on Climate Change (IPCC) forecasts a rise of up to 1 metre during this century (dark green shading above). Other researchers consider that a rise of as much as 180 cm is possible (light green shading above). As there are numerous studies and scenarios to back up both these projections, the findings and figures cover a broad range. There will certainly be feedback effects between the melting of the glaciers and the expansion of water due to global warming. Record rates of sea-level rise are predicted in the event of more rapid melting of the Antarctic and Greenland ice sheets.

How nature and humankind alter the coasts

> Coastlines are shaped by natural forces, often changing greatly in response to changing environmental conditions. On the other hand, humans also influence the coastal realm. They colonize and cultivate the coastal zones and excavate raw materials. Such interventions mesh with geological and biological processes, precipitating the most varied changes.

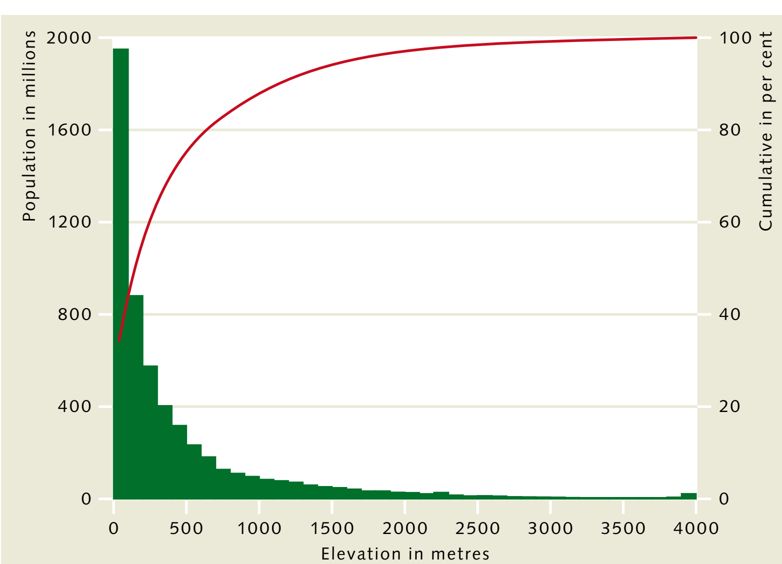
Importance and characteristics of coastal zones

The coast is the interface between the land, ocean and atmosphere. There is no standard definition of what constitutes "the coast" because it depends largely on one's perspective or the scientific question – the coastal zone can be considered more the sea, or more the land. Simply stated, the coastal zone encompasses that area where the land is significantly influenced by the sea, and the sea is notably influenced by the land. This is a complex space that is also strongly impacted by human activity. The coastal zones of the Earth are extremely diverse and tremendously important, not only for humankind.

- They cover around 20 per cent of the Earth's surface;
- They are the site of vital transport routes and industrial facilities;
- They are prime recreation and tourist areas;
- They are a resource for minerals and geological products;
- They contain important ecosystems with large species diversity;
- They function as an important sediment trap that consolidates sediments from the rivers;
- They influence many global parameters in their role as a buffer between the land and sea;
- 75 per cent of the mega-cities with populations over ten million are located in coastal zones;
- 90 per cent of the global fishery activity occurs in coastal waters;
- They are the place where more than 45 per cent of the world's population lives and works.

A large portion of the world population lives in flat coastal areas that can drastically change their shape within a short time. The populations in coastal zones are growing faster than in any other region on Earth. Coastal cities are expanding accordingly. People are claiming more and more land. At the same time they are making more intensive use of the coasts, for example by developing large wind-energy farms in the sea.

3.5 > Population distribution by elevation



Sediments shape the coasts

The shape of a coast is influenced by many factors. One important factor is the shifting of sediments, such as mud, sand and gravel. The sediments are primarily transported by wind-induced waves and water currents – either tidal currents, or rivers that flow into the sea. Depending on the currents, sediments are either eroded,

3.6 > Tidal currents on the coast of the Isle of Lewis, off the west coast of Scotland, have carried away the sand and left the stony ground exposed.

redistributed or deposited (accumulation). If sediments are carried away instead of being redeposited, the shape of the coast will change over time. One example of this is the East Frisian island Memmert, where currents caused so much erosion on the southwest side that the old lighthouse was standing in water until it was finally demolished. Another example is seen on the western beach of the Danish North Sea island Rømø. It is continually growing wider due to sediment input.

In principle, there are two main directions of sediment transport. One of these is parallel to, or along the coast. The other direction is either toward or away from the coast. The more sediment that is eroded or deposited, the more strongly the coastal form changes. The rate at which sediment can be eroded depends on its composition, as well as on the intensity and persistence of the wind and water currents. A strong storm tide can wash away immense amounts of sediment within a few hours. On hard, rocky coasts, which are more resistant to erosion than loosely deposited sand, the shape of the coastline changes comparatively slowly. A coast usually recedes as a result of erosion: More sediment is lost than is replaced by the currents. The developmental status of a coast, however, is not defined by its sediment balance alone. There are coastal areas that are stable over the long term because sediment is simply transported along them. In many coastal regions today, the natural input of sediments is hampered by construction projects such as dams. Only 20 per cent of the coastal regions worldwide are made up of loose materials such as sand, mud or gravel, but more than half of these coasts are suffering from erosion today. Of course, the loose-material coasts generally adapt quickly to changes because the sediments are redistributed relatively easily – material deficits at one place are balanced again by new sediment input. Yet whether the character of such a coast is preserved in individual cases is essentially dependent on the rate of sea-level rise, stability of the sediment, and sediment

3.7 > The old lighthouse on the East Frisian island of Memmert once stood in the dunes, but was washed out by erosion over the course of decades.

input. Even coastal protection measures do not only contribute to the preservation of the coasts. They can also alter the coasts. It is even very possible that by attempting to protect one segment of a coastline, another area is damaged. When one area is protected from erosion by construction of a breakwater, an adjacent, non-protected area may be deprived of its essential sediment input. Compared to sandy coasts, sea-level rise will have a less severe impact on steep and especially rocky coasts. Worldwide, steep and rocky coastlines make up about 80 per cent of all coasts.

Sediments cause the Earth's crust to sink

It is clear that coastal areas subside under the weight of the glacial masses placed there in ice ages. But sediments can also accumulate in such thick layers that they press down on the lithosphere, the Earth's crust. This subsides initially and then rises again later when the load is removed. In the case of glaciers, this happens when the ice melts at the end of an ice age. The rebound movement can last for several tens of thousands of years. An example of this can be seen on the Scandinavian land mass, which is still rising today by up to 9 millimetres a year. Sometimes the Earth's crust rebounds unevenly, so that one part is still sinking while another is rising.

Thick sediment packages are often deposited in delta regions where the rivers transport enormous quantities of sediment to the sea. Because of the stacking of sediments, the lithosphere gradually yields to the pressure. The subsiding bedrock thus produces a rise in sea level relative to the land. In some cases this isostatic subsidence is compensated by the gradual upward increase in sediment thickness. In other cases, however, the sediment itself is compressed by the increasing load so that the land mass still sinks.

Humans can also accelerate the subsidence, for instance by extracting groundwater, oil or natural gas, as in the Niger Delta. There are regions where the land surface is falling by up to 5 cm per year due to the combined effects of these factors. Relative sea level rises there accordingly.

Humans mould the face of the coasts

Over the past 8000 years, during the final phase of sea-level rise after the last ice age, sedimentation has contributed enormously to the development of the coasts. Coastal land areas grew by the deposition of transported material, and in some regions large river deltas were formed. Rivers are very important transport paths for carrying sediments to the coasts. The volume that they carry depends on several factors:

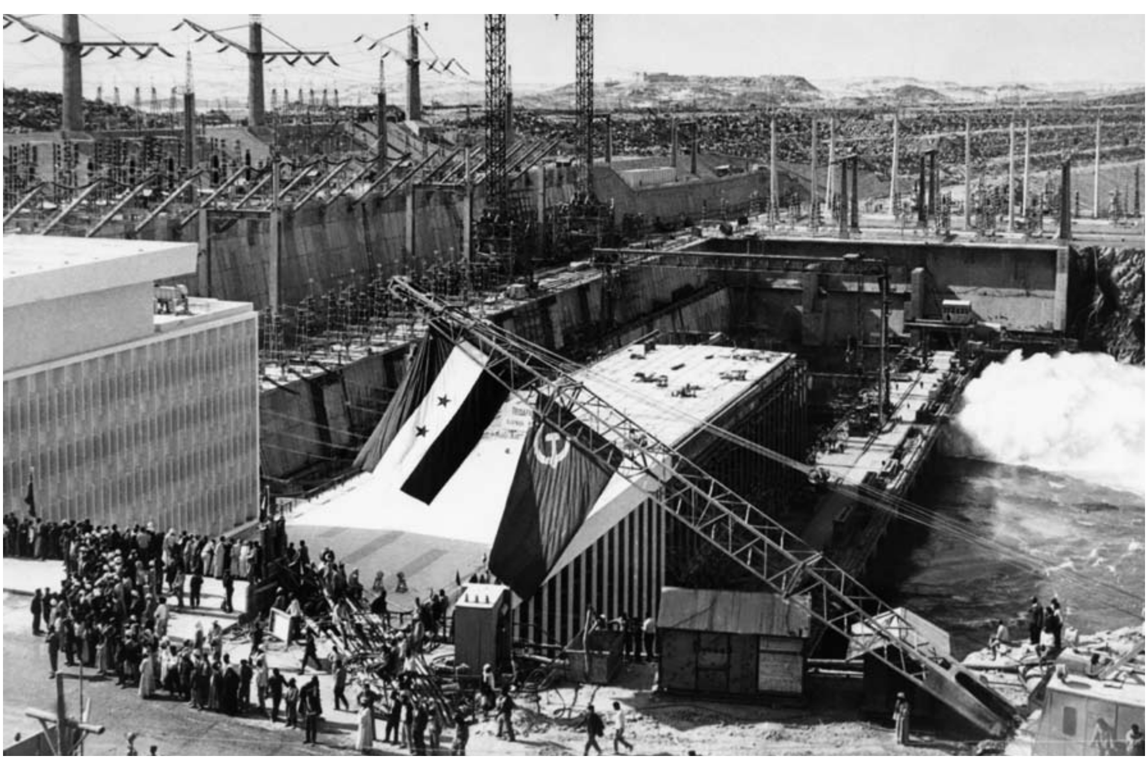
- The size of the catchment basin from the source to the estuary;
- The relief in the catchment basin (rivers in high-relief mountainous areas transport more sediment than rivers that flow through flatlands);
- The rock and sediment characteristics (for example, grain size) or the amount of available sediments from weathering and mechanical erosion;
- The climate in the catchment area and its impact on weathering;

- The amount of surface water flowing downstream and the storage capacity of the soil (how much water flows also depends on the amount of precipitation, which is, in turn, dependent on climate).

Forest clearing, overgrazing and imprudent farming practices lead to severe soil erosion, especially in tropical regions. If the sediments are not blocked by dams, they are mostly deposited in coastal regions. This can have consequences. For one, the sediments can cloud the water, change the water quality, and thus severely impact living organisms in the water. Turbidity also decreases light penetration and thus lowers the **primary productivity.**

On the other hand, high erosion could also lead to algal blooms because large amounts of nutrients in the rivers flow into the coastal waters with the sediments. When these algae die, they are broken down by microorganisms that consume oxygen. This can create lethal low-oxygen zones and consequently species diversity drops in these areas.

By contrast, many regions are plagued by a paucity of sediments because the water is held back by dams. Worldwide over 41,000 large dams are in operation. There are also many smaller dams and water reservoirs. Together, they block 14 per cent of the total global river flow, as well as enormous volumes of sediment. This is a severe loss for the replenishment of the coasts. Erosion increases. This sediment deficit is fatal in places where the basement is subsiding beneath the old, heavy sediment packages. New sediment is lacking that would normally be deposited to compensate for the subsidence. If the land sinks, saltwater gradually intrudes into the estuary and adds salt to the groundwater. The Nile is a good example of this. Before construction of the Aswan Dam, recurrent annual floods washed fertile sediments from the interior of the continent into the Nile Delta on the Mediterranean Sea. Not only were the sediments essential for the farmers on the banks of the Nile, they were also crucial to compensating for subsidence in the heavy delta region. After the dam was built in the 1960s,



3.8 > With the beginning of operations in 1968, the Aswan Dam was celebrated as a masterpiece of technology. At that time nothing was known about environmental impacts such as land salination on the coasts. The dam was officially opened in 1971. Its construction took around eleven years.

the flooding and transport of sediments came to a halt. This resulted in sustained harvest reduction and massive coastal erosion. Similar problems can be expected in China's Yangtze Delta because of the recently completed Three Gorges Dam.

Recent investigations on the North American Atlantic coast, based on interpretations of satellite photos and topographical maps covering a period of over 100 years, suggest that rising sea level also disturbs important sedimentation processes and will lead to changes on the coasts. It is believed that a sea-level rise of 1 metre will result in an average retreat of the coastline by about 150 metres. This presumes, according to the researchers, that the sediment balance (erosion and deposition) is in a state of equilibrium. The examples cited here, however, clearly show that that is not the case. For the calculations, therefore, one would at least have to consider the sediment transport along the coasts and changes in the sedimentation balance that sea-level rise would cause. So far that has not been done. The coastal retreat could therefore be even more drastic.

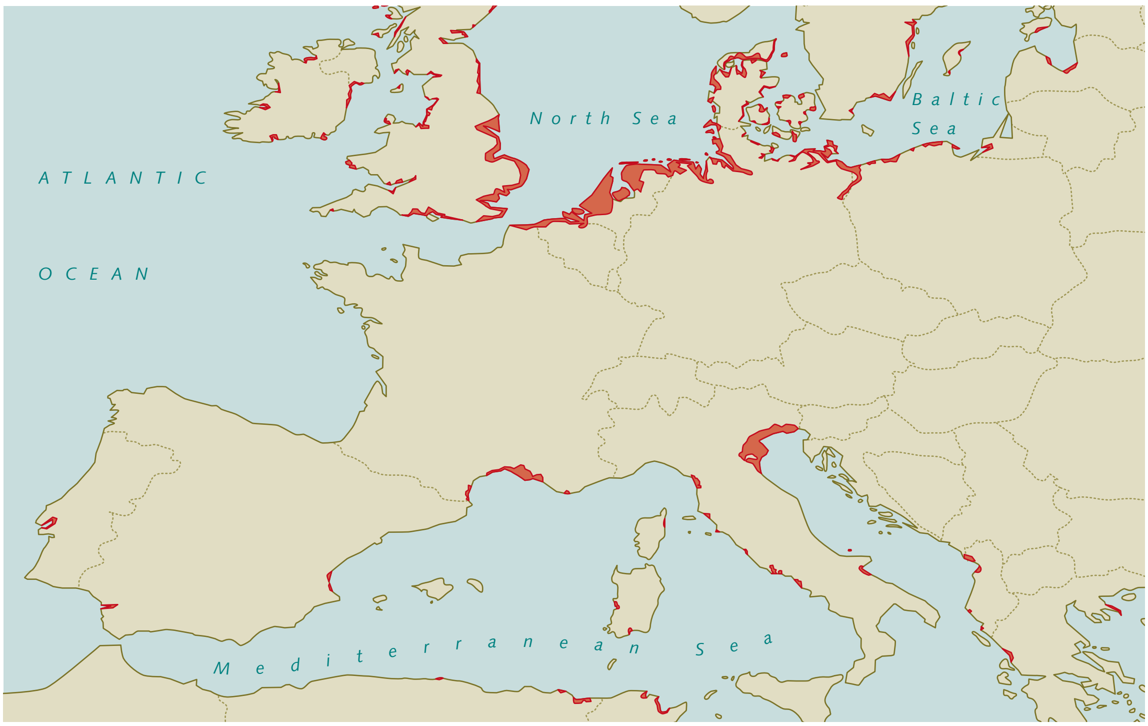
3.9 > At times of especially high water levels in the Lagoon of Venice some areas of the city, like the Piazza San Marco, are repeatedly flooded. Italians call the high water acqua alta.

Hydrologic engineering impacts

In many estuarine regions there is an alternating in- and outflow of seawater in phase with the tides, and thus a mixing of saline water with the fresh water continuously flowing out from the rivers. Suspended sediment from the land and sea can be deposited when the current-energy level drops. The sediment budget is subject to a very sensitive balance. The building of dams, deepening of channels, or other construction can severely disturb this balance. The impacts are often very serious.

Among other activities, the deepening of channels is highly controversial today. 95 per cent of global commerce depends on shipping. For logistical reasons most of the world's large harbours are located on river estuaries. The ever-increasing sizes of the ships used, with their corresponding deep draughts, require deeper channels. Additionally, the shipping routes are stabilized by structures on the banks, and current flow is optimized by control structures. The deepening of channels can release pollutants trapped in the sediments. In addition, the flow rates can increase, which also increases sediment redistribution.

Due to the larger volume of water flowing in and out, the tidal range can also increase. This further affects the sediment budget, because more rapidly flowing water has more energy for moving sediments. Sea-level rise and high-water events amplify these effects. There is already concern about how this impacts the structural integrity of the river dams. The high volume of ship traffic exacerbates the situation because the ships' wakes often erode the river banks. The removal of sediment or sand, which is a common procedure on the island of Sylt for beach restoration, changes the shape of the sea floor. In the



3.10 > If the coasts were not protected by dikes, sea-level rise of 2 metres would produce this picture. The red-coloured areas would be permanently inundated. According to current predictions sea level could rise by as much as 180 cm by the end of this century.

long term this can definitely have an impact on the protection of the coasts. It is possible that deepening the seafloor could shift the wave-break zone to a position closer to shore.

The removal of large quantities of sand would also change the habitats of marine organisms. This is similarly the case in the reverse situation when sand is discharged into the sea, for instance when dredged material is dumped onto the sea floor. 80 to 90 per cent of these sediments originate from operations related to channel deepening. Hundreds of millions of cubic metres of sediment are dumped annually worldwide. If they are not able to escape, marine organisms living in the dumping areas are covered up.

Coastal city growth

Human societies also damage the biotic environment through the tremendous growth rates of coastal cities. New land areas are often created in the sea to make room for the overflowing development. Many large projects worldwide, including the airport in Hong Kong, have been built in this way. For that project an area of over 9 square kilometres was filled. The harbour at Tianjin in China was even larger, appropriating around 30 square kilometres of marine area. These encroachments have significant impacts on the directly adjacent coastal zones. For example, fill material covering 180 hectares used in construction of the Nice airport triggered a disastrous landslide in 1979. This then caused a tsunami that took the lives of 23 people.

Climate change alters the coasts

In order to accurately predict the future fate of coastal regions, researchers must first determine whether the present measurable changes are actually a consequence of climate change or an expression of natural climate variability. We can only speak of climate change if climate-related changes are statistically discernable from natural fluctuations. Climate change is thus not equivalent to climate variability. Scientists hence need to have measurements and observations covering representative time intervals.

We already know that global warming will not lead to uniform increases of air and water temperatures everywhere, and the change is not restricted to temperature changes. The consequences of climate change can be highly variable. This is clearly illustrated in the following examples.

Melting of sea ice and thawing of permafrost grounds

Sea ice in the sub-polar and polar coastal waters acts as a buffer between the atmosphere and seawater. It prevents storms from creating waves that would roll into the coasts and remove sediments. If the ice masses shrink by thawing, this buffering effect is lost. Sediments that were previously protected by the ice cover are also more strongly eroded. Permanently hard-frozen soils, called **permafrost grounds,** thaw out. These are also more easily eroded by wind and waves on the coasts than the frozen land masses. On the other hand, erosion typically caused by icebergs and glaciers no longer occurs.

High tide and spring tides
Mean high tide refers to the average high-water level at a particular location on the coast. Flood tides that reach especially high above the mean high tide are referred to as spring tides. These occur regularly, corresponding to certain alignments of the sun and moon. It is particularly dangerous for the German North Sea coast when heavy storms from the west coincide with the spring tides.

Changes in freshwater balance, precipitation and sediment input

Climate change will presumably lead to the melting of continental glaciers, while at the same time the amount of new snow required for maintaining the glaciers will probably decrease. Over time this will also lead to a decline in the amount of freshwater flowing from the mountains. Water shortages could result. People could respond by increasing the amount of water held in reservoirs. This, however, would result in less fresh water and sediments being transported to the ocean. At the same time, in other areas, increased precipitation is expected as a consequence of global warming, for example, in the **monsoon regions** of the world. The strong monsoon rains and water discharge will lead to increased flooding and the transport of large amounts of sediments and nutrients by rivers into the coastal seas.

Island and coastal flooding

The rise in sea level caused by climate change will lead to flooding in many coastal areas and island groups. It is expected that these regions will not be just temporarily, but permanently submerged. These floods thus cannot be equated with the short-term, episodic flooding of land areas that will occur more frequently in the near future. Sea-level rise could reach the two-metre mark as early as the next century or soon thereafter.

This scenario, however, is based on topographic data alone. It does not take account of dikes and other protective structures. Simulations simply allow the water to flow over the coastal contours. This model also does not consider the increased removal of land by coastal erosion, which will probably accompany rising sea level. Complete coastlines, along with their surf zones, will likely shift landward due to the erosion. The destructive power of the water will then be unleashed on areas that were previously protected. Today, storm floods are already tearing out protective vegetation. These negative effects will only intensify in the future. The very gently rising coastal slopes, where the surf can gradually roll up to the land, are becoming steeper. The steeper coastal foreland presents a greater surface area of vulnerability for future storms to assault. Erosion gains dynamic momentum. The buffering capacity of the coastal foreland decreases.

Threatened regions also include many areas that are presently protected by dikes. For dike structures on the North and Baltic Seas the crown height is designed to be 30 to 90 cm above the maximum storm event height, as a safety factor in consideration of future sea-level rise. This will not be sufficient, however, for a sea-level rise of 2 metres. Many densely settled areas in the North Sea area today already lie below the mean high-tide level, and in the Baltic Sea area at around the present-day sea level.

Other coastal areas are characterized by complex and important ecosystems. These produce biomass that sometimes has a direct impact on the shape of the coast. For example, the growth of corals can create new islands. Coral banks are also important bulwarks that break the surf. In some cases the growth of corals can even compensate for the rise of sea level. Whether the formation of new corals will be able to keep up with the rise of sea level in the future depends on the rate of the rise as well as on water temperature. Researchers are concerned that living conditions for the adaptable but sensitive corals will become worse; firstly, because the water temperature in some areas is already too high today and, secondly, because the corals will not be able to keep up with the projected sea-level rise or possible subsidence of the coasts.

Other shallow coastal segments, such as estuarine areas, mangroves and marshes, which themselves provide natural protection against storm floods, are also threatened by flooding. In case the mangroves and marshes sink, waves can encroach onto the land and cause considerable damage. Only in very rare and uncommon cases could such changes be compensated by sediment input from inland.

Extreme water levels

It is now believed that extreme weather events such as tropical storms and storm surges will occur more frequently due to global warming. These will likely intensify the impacts of sea-level rise because when sea level is higher the destructive capacity of a storm on the coast is much greater. Scientists expect to see increased storm activity particularly in the temperate and tropical regions. There is still no consensus as to whether the frequency of storm activity will increase worldwide, because different scientific computer models and measurement data have yielded different results.

Storm floods originate through the interplay of storm systems and tides. When storm winds push the water toward the coasts during flood tide, especially during spring flood, the risk of flooding for large land areas is greatly increased. Such storms can last for several days and cause the water to rise so high that it does not abate even during the ebb tide.

Storms can also have severe effects in marginal seas such as the Baltic Sea, where the tidal ranges are minimal. Just like in a bathtub, the wind piles water masses up in one part of the basin, and when the wind abates or changes direction they slosh back. If the wind then blows in the opposite direction, the two factors can amplify the effect. As a consequence the water level on the German Baltic Sea coast can rise by more than 3 metres. Heavy precipitation can even intensify this situation because the rainwater or high water from the rivers cannot flow off due to the already high water level on the coast.

Increasing incidence of high water

There are other factors related to sea-level rise besides just increased water levels. It is of critical importance that unusually high storm-surge levels are occurring more often, as the example of the threat for Germany illustrates. With a sea-level rise of 1 metre, dangerous storm surges will occur more often because the base level is then a metre higher. In this case, a 100-year high-water level, like the storm flood of 1976 on the German North Sea coast, could take place every ten years. The probability of recurring severe storm surges would increase significantly. On the German Baltic Sea coast with its lower storm-flood levels, this effect would be even more pronounced. A 100-year high-water level with an elevation of 2.5 metres above **mean sea level** (German: Normalnull, NN) would occur every 2 to 5 years there.

3.11 > The storm surge of 1976 is notable as the most severe storm flood ever recorded on the German North Sea coast, and failure of the dike, as seen here on the Haseldorfer Marsh on the Elbe River, caused extremely severe damage. The water level in Cuxhaven reached a record high of 5.1 metres above normal. Nonetheless, the consequences were less severe than those of the flood of 1962 because many segments of the dike had been reinforced in the meantime.

The battle for the coast

> More than a billion people – most of them in Asia – live in low-lying coastal regions. During the course of this century some of these areas could be inundated by rising sea levels. The inhabitants will be forced to find ways of coping with the water or to abandon some areas altogether. For some time now experts have been trying to establish which regions will be the hardest hit.

The million dollar question: how bad will it be?

Climate change is placing increasing pressure on coastal regions which are already seriously affected by intensive human activity. This raises the question of whether – or to what extent – these areas will retain their residential and economic value in the decades and centuries to come, or whether they may instead pose a threat to the human race. Also, we do not know what changes will occur to the coastal ecosystems and habitats such as mangroves, coral reefs, seagrass meadows and salt marshes that provide the livelihood of coastal communities in many places.

Scientists have tried in various studies over recent years to assess the extent of the threat posed by sea-level rise. To appreciate the coastal area at greatest risk of flooding, it is necessary to first analyse current heights above sea level. This is not easy because no reliable topographical maps yet exist for many coastal areas. At a rough estimate more than 200 million people worldwide live along coastlines less than 5 metres above sea level. By the end of the 21st century this figure is estimated to increase to 400 to 500 million.

3.12 > Bangladesh experienced the full force of Cyclone Aila in 2009. Thousands of people lost their homes. This woman saved herself and her family of five in a makeshift shelter after the gushing waters burst a mud embankment.

During the same timeframe the coastal megacities will continue to grow. New cities will be built, particularly in Asia. In Europe an estimated 13 million people would be threatened by a sea-level rise of 1 metre. One of the implications would be high costs for coastal protection measures. In extreme cases relocation may be the only solution. A total of a billion people worldwide now live within 20 metres of mean sea level on land measuring about 8 million square kilometres. This is roughly equivalent to the area of Brazil. These figures alone illustrate how disastrous the loss of the coastal areas would be. The Coastal Zone Management Subgroup of the IPCC bases its evaluation of the vulnerability of coastal regions, and its comparison of the threat to individual nations on other features too:

- the economic value (gross domestic product, GDP) of the flood-prone area;
- the extent of urban settlements;
- the extent of agricultural land;
- the number of jobs;
- the area/extent of coastal wetlands which could act as a flood buffer.

A quite accurate estimate has now been made of which nations would suffer the most because a large percentage of the population lives in coastal regions. Bangladesh and

3.13 > On the North Sea island of Sylt, huge four-legged concrete "tetrapods" are designed to protect the coast near Hörnum from violent storm tides. Such defence measures are extremely costly.

Climate change threats to the coastline of northern Germany

Northern Germany's coastline extends over about 3700 kilometres. The North Sea coast and islands account for about 1580 kilometres, and the Baltic Sea coast including the Bodden waters (a local term for shallow coastal waters) and islands about 2100 kilometres. The low-lying North Sea areas less than 5 metres above sea level are considered to be under threat, as are the areas along the Baltic Sea coast less than 3 metres above sea level. This equates to a total area of 13,900 square kilometres, a large proportion of which is currently protected by dykes. About 3.2 million people live in these flood-prone areas. The economic value of these regions currently amounts to more than 900 billion euros. There are also more than a million jobs here. Most vulnerable to storm floods and storm tides are the major cities, which include Hamburg and Bremen in particular in the North Sea region, and Kiel, Lübeck, Rostock and Greifswald along the Baltic Sea. Coastal erosion is threatening many tourist centres on both coastlines. Furthermore large sections of the ecologically-valuable saltmarshes and intertidal mudflats could be lost in the long term. It is safe to say that the cost of coastal protection measures will rise, particularly dyke construction and beach nourishment.

Vietnam are extremely vulnerable. Nearly all the population and therefore most of the national economy of the low-lying archipelagos of the Maldives and the Bahamas are now under threat. In absolute numbers China is at the top of the list.

The most vulnerable regions in Europe are the east of England, the coastal strip extending from Belgium through the Netherlands and Germany to Denmark, and the southern Baltic Sea coast with the deltas of Oder and Vistula rivers. There are also heavily-populated, flood-prone areas along the Mediterranean and the Black Sea, such as the Po delta of northern Italy and the lagoon of Venice as well as the deltas of the Rhône, Ebro and Danube rivers.

Some densely-populated areas in the Netherlands, England, Germany and Italy already lie below the mean high-water mark. Without coastal defence mechanisms these would already be flooded today. For all these regions, therefore, the question of how fast the sea level will rise is extremely important and of vital interest. We need to resolve how we can intensify coastal protection right away, how society can adapt itself to the new situation, and whether it might even be necessary to abandon some settlements in the future. Without appropriate coastal protection, even a moderate sea-level rise of a few decimetres is likely to drive countless inhabitants of coastal areas in Asia, Africa and Latin America from their homes, making them "sea-level refugees". The economic damage is likely to be enormous. The infrastructure of major harbour cities and especially regional trading and transportation networks – which often involve coastal shipping or river transport – would also be affected. Experts have prepared a detailed estimate of the implications of rising sea levels on Germany's coastlines.

An old saying for tomorrow: Build a dyke or move away

Ever since first settling along the coast, human societies have had to come to terms with changing conditions and the threat of storms and floods. Over time they developed ways of protecting themselves against the forces of nature. Today four distinct strategies are used, none of them are successful in the long term:

3.14 > The Netherlands is readying itself for future flooding. Engineers have constructed floating settlements along the waterfront at Maasbommel. Vertical piles keep the amphibious houses anchored to the land as the structures rise with the water levels.

1. Adaptation of buildings and settlements (artificial dwelling hills, farms built on earth mounds, pile houses and other measures);
2. Protection/defence by building dykes, flood barriers or sea walls;
3. Retreat by abandoning or relocating threatened settlements (migration);
4. "Wait and see", in the hope that the threat abates or shifts.

A culture of risk developed early on in Europe and parts of East Asia (Japan, China). Phases of retreat and adaptation until the Middle Ages were followed in more modern times by a strategy of defence; a strategy adopted in North America and other areas which were settled later. The effective protection of low-lying regions and coastal cities from flooding, land loss, water-logging and groundwater salinity is a both costly and technologically complex process. However, the example of the Netherlands shows that a small and affluent industrialized nation, when faced with a serious potential threat, is certainly capable of following the strategy of defence over the long term – after all, virtually two thirds of its country lies below the mean high-water mark. Germany also invests heavily in maintaining and protecting its much longer coastline with dykes and other structures. Each year the Netherlands and Germany together spend about 250 million euros on coastal defence. Although this amounts to only 0.01 per cent of the German and 0.05 per cent of the Netherlands' gross national income, it should not be forgotten that these amounts are utilized for the maintenance and/or fortification of existing defence works. Much poorer coastal and small island states are not in a position to protect their coastlines on a similar scale. Confronted with rising sea levels they have the choice of either adapting or retreating. But even resettlement projects like that of the Carteret Islands, part of Papua New Guinea, which began in 2007, are costly. It is not yet possible to accurately assess the exact cost of evacuating 1700 people, but this will certainly amount to several million US dollars.

Effects of sea-level rise on natural coastal systems		Possible protective/adaptive measures	Relative costs
1. Flooding of low-lying areas and resultant damage	a) Storm tides b) Backwater in estuaries	1. Dykes and flood barriers [P] 2. Artificial dwelling mounds, flood-proof building (standards) [A] 3. Identification of risk zones [A/R] 4. Adapted land-use and landscape planning [A/R]	1. Very high (construction, maintenance) 2. Medium to high 3. Very low (one-off) 4. Medium (recurrent)
2. Loss of or changes to coastal wetlands		5. Adapted land development planning [A/R] 6. Dyke relocation [A/R] 7. Foreshore reclamation [P/A] 8. Beach nourishment, sediment protection [P]	5. Low to medium (ongoing) 6. Very high (one-off) 7. High (recurrent) 8. Medium/low (ongoing)
3. Direct and indirect morphological changes, particularly erosion of beaches and bluffs		9. Construction of groynes, bank protection, sea walls [P] 10. Beach nourishment, dune protection [P] 11. Underwater reefs, breakwaters [P] 12. Development-free zones [R]	9. Medium to high (construction) 10. Medium/low (ongoing) 11. Medium to high (construction) 12. Low to high (one-off)
4. Intrusion of saltwater	a) into surface water b) into ground water	13. Dams and tide gates to prevent influx of saltwater [P] 14. Adapted/reduced withdrawal of water [A/R] 15. Pumping in of freshwater [P] 16. Adapted withdrawal of water [A/R]	13. High (construction, maintenance) 14. Low (ongoing) 15. Medium (recurrent) 16. Low (permanent)
5. Higher (ground)water levels and limited soil drainage		17. Soil/land drainage improvement [P] 18. Construction of pumping stations [P] 19. Altered land use [A] 20. Designation of flood areas/ high risk areas [A/R]	17. High (ongoing) 18. Very high (construction, maintenance) 19. Low (permanent) 20. Very low (recurrent)

3.15 > Rising sea levels impact differently on coastal areas and their inhabitants. Societies may take steps to protect themselves, but the costs can be substantial and ultimately exceed the benefits. The measures are classified as: [P] – Protective, [A] – Adaptive, and [R] – Retreat measures

Top ten nations classified by population in low-lying coastal regions			Top ten nations classified by proportion of population in low-lying coastal areas		
Nation	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions	**Nation**	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions
1. China	127,038	10 %	**1. Maldives**	291	100 %
2. India	63,341	6 %	**2. Bahamas**	267	88 %
3. Bangladesh	53,111	39 %	**3. Bahrain**	501	78 %
4. Indonesia	41,807	20 %	**4. Suriname**	325	78 %
5. Vietnam	41,439	53 %	**5. Netherlands**	9590	60 %
6. Japan	30,827	24 %	**6. Macao**	264	59 %
7. Egypt	24,411	36 %	**7. Guyana**	419	55 %
8. USA	23,279	8 %	**8. Vietnam**	41,439	53 %
9. Thailand	15,689	25 %	**9. Djibouti**	250	40 %
10. Philippines	15,122	20 %	**10. Bangladesh**	53,111	39 %

3.16 > Nations with the largest populations and the highest proportions of population living in low-lying coastal areas. Countries with fewer than 100,000 inhabitants are not included. Also excluded are 15 small island states with a total of 423,000 inhabitants.

There are different strategies for combating and coping with the effects of rising sea levels. Whether a measure is used at a regional or local level depends mainly on the cost and the geological features of the area. In the Ganges-Brahmaputra delta region of Bangladesh for instance, heavy sea dykes would sink into the soft subsoil. Also, there is no money available to erect hundreds of kilo-metres of dykes. Such a project is likely to cost more than 20 billion euros – at least a hundred times more than the annual coastal defence costs of the Netherlands and Germany combined. The national economy of Bangladesh could not support anything like this amount. In other areas there are simply not enough building materials to protect the coast. Many coral islands do not have the sediment they need to hydraulically fill the coastline, or the space and building materials for dykes and sea walls. Even if enough cash were available, these islands would still be largely defenceless against the sea. The threat from rising sea levels is worsened by the fact that coralline limestone is being removed from the reefs and used to build hotel complexes.

It is impossible to foresee with any accuracy what the rising sea levels will mean for coastal and island nations and their defence in the 21st century, as this largely depends on the extent and speed of developments. If they rise by much more than 1 metre by 2100, then the dykes and protective structures in many places will no longer be high enough or stable enough to cope. New flood control systems will have to be built and inland drainage systems extensively upgraded. Experts anticipate that the annual costs of coastal protection in Germany could escalate to a billion euros – to protect assets behind the dykes worth 800 to 1000 billion euros. On a global scale the cost could be a thousand times greater. Although the costs of defence and adaptation would appear worthwhile to some nations in view of the substantial economic assets protected by the dykes, the poorer coastal areas will probably be lost or become inhabitable. The inhabitants will become climate refugees.

Presumably the industrialized countries are capable of holding back the sea for some time using expensive, complex coastal protection technology. But even there, this strategy will ultimately have to give way to adaptation or even retreat. Extremely complex defensive fortifications such as the flood barriers of London, Rotterdam and Venice are likely to remain isolated projects. For most other areas the development of modern risk management concepts would be more logical.

Conclusion

The future of the coast – defence or orderly retreat?

The shape of coastal zones is governed by a balance of different factors such as erosion stability, sedimentation, tides, storm frequency and ocean currents. Climate change, rising sea levels and human activity can disturb or intensify these factors and influence the equilibrium of the coasts. Such imbalances can usually be compensated for, to a certain crucial tipping point. Once this point is reached any changes are irreversible, and a return to the natural equilibrium is no longer possible. The combined effect of human activity and climate change are pushing many coastal areas towards their tipping point. In future, therefore, all building activity and the moving of substances such as dredged material must be planned very carefully with a thought to sustainability. This calls for an integrated coastal zone management system. Without doubt sea levels will rise slowly at first, speeding up and continuing well beyond the 21st century. Gradually, many coastal areas will become uninhabitable. People will lose their homes and a part of their culture. Affluent coastal nations will be able to slow down this process for some time, but will have to invest enormous financial and technical capital on measures of protection and adaptation. For the present time Germany will not depart from its strategy of defence along the coastlines of the North and Baltic Seas. The cost-benefit ratio of coastal protection (for people and material assets) is favourable. However, here too the population will in the long term be forced to decide whether to retreat from these coastal areas or to adapt to the advancing sea. Architects in the Netherlands are already building the first floating settlements which, firmly anchored to the land, can float at high tide. This is a good example of the strategy of adaptation – people are learning to live with the water. In future people in many places will have to adopt similar sustainable land-use and development planning strategies. This applies particularly to the severely threatened shorelines below 5 metres. It is also conceivable that buffer zones will be established in settlement areas, where building will be allowed only in accordance with certain low-risk specifications. In some flood-prone areas no high-quality homes or businesses may be located on the ground floor even today. In the medium term, however, there is one main objective: to limit climate change and sea-level rise as much as possible by taking action to mitigate climate change.

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